

# NEAR Shoemaker's Low Altitude Operations at Eros

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On February 14, 2000, NASA's Near Earth Asteroid Rendezvous Shoemaker (NEAR) spacecraft inserted into orbit around 433 Eros becoming the first spacecraft to orbit an asteroid. After nearly 8 months of orbiting the irregularly shaped Eros at distances ranging from 367 to 34 km, the dynamical environment of Eros including its mass, gravity distribution, shape, pole direction and spin had been well characterized. Plans were then begun to obtain close observations ( $< 5$  km) of Eros' surface towards the end of NEAR's mission and eventually land the spacecraft on Eros [1, 2]. To prepare for these end-of-mission operations, a close flyby orbit was designed and executed on October 26, 2000 when the NEAR spacecraft safely flew within a distance of 5.5 km near the  $0^\circ$  longitude (long) end of Eros' elongated body ( $-21.52^\circ$  Latitude,  $328.8^\circ$  E. Longitude). The timing and accuracy of the maneuver to initiate the flyby was critical to achieve the desired flyby location and the post-flyby orbital conditions. This flyby was significant not only because it was the closest any spacecraft had ever flown past an asteroid, but also because it demonstrated the theory that a flyby of an ellipsoidal asteroid's trailing edge would increase the spacecraft's orbital energy [1, 3]. This was evident by observing the change in the orbit osculating semi-major axis which increased from 35 km to 41 km after the flyby.

Several close flybys of the ends of Eros were then designed during four consecutive days near the end of January 2001. To simplify the planning of these orbits no special surface locations were targeted. The spacecraft was placed into an elliptical 36 km x 22 km equatorial orbit (retrograde) on January 24, 2001 with an 0.5 m/s Orbital Correction Maneuver (OCM-21). The advantage of this orbit was that it allowed the possibility of two close flybys ranging from 4.4 - 7 km of both ends of Eros during each periapsis passage without placing any requirements on the time of the maneuver to initiate it. This orbit configuration was relatively stable since the dynamical interaction with the asteroid's ends are in general minimized for equatorial orbits[1]. What had been believed to be a relatively easy orbit design for navigation in achieving close imaging of Eros' surface actually turned out to be a difficult task as far as producing consistent orbit predictions weeks in advance. These orbit predictions were needed by the Sequencing Team for scheduling the imaging and downloading the images on the allocated 70 meter Deep Space Network (DSN) antennas. The reasons for these difficulties will be discussed in the paper. To finish this close flyby phase, a small maneuver, OCM-22, was then executed near apoapsis to dip the spacecraft even closer to the surface upon the next periapsis passage. On January 28, 2001, NEAR Shoemaker broke its prior close flyby records and flew within 2.7 km of the asteroid's surface enabling imaging resolutions of 30 cm/pixel. Because this orbit was not stable and the orbital period was less than 13 hours, a post-flyby maneuver (OCM-23) had to be preprogrammed on-board the spacecraft to circularize the orbit at apoapsis. This paper will further discuss the design and navigation of the NEAR Shoemaker spacecraft's low altitude passes.

With this close flyby phase over, final preparations for landing NEAR Shoemaker on Eros had begun by placing the spacecraft into a relatively benign 35 km equatorial orbit for nearly 2 weeks prior to touchdown. Finally, on February 12, 2001 after a 4.5 hour controlled descent using five open-loop maneuvers, the NEAR Shoemaker spacecraft safely landed on the surface of Eros becoming the first spacecraft ever to touchdown on an asteroid. This landing was made extraordinary by the fact that the spacecraft was not designed for landing and it remained in contact with NASA's Deep Space Network after the landing. The descent trajectory was designed primarily to acquire as many close range high resolution images ( $< 1$  km) as possible while providing optimal viewing geometries and secondarily to ensure the safety of the spacecraft by minimizing its impact velocity. Since the spherical harmonic representation of Eros' gravity diverges below the sphere circumscribing the asteroid ( $< 18$  km), a polyhedral gravity field based on our Eros shape determination was used for integrating the trajectory below this limit. In order to

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maximize the number of images downlinked and to acquire images as close as possible to the surface, the high gain antenna had to remain Earth pointing. Since the science instruments, high gain antenna and solar arrays are fixed to the spacecraft, this requirement constrained the imaging camera to point perpendicular to the Earth direction through a roll about the Earth vector during the descent. The direction of the descent (nearly the camera pointing direction) relative to the asteroid and Earth directions allowed for optimum low emission angles for imaging. The first maneuver to initiate the landing sequence, EMM-1, was used to change the plane of NEAR's orbit from equatorial and target the beginning of the descent trajectory at the 35° South latitude. The four braking maneuvers (EMM-2 – 5) were designed to slow the spacecraft descent speed, maximize imaging time and minimize impact speed. To further reduce the probability of damaging the spacecraft during touchdown, we picked the landing site on the rim of a large depression known as Himeros (-35.6° latitude, 82.1° E. Longitude) because of its smooth terrain, scarcity of large boulders and scientific interest. Redundant 70 meter DSN antennas between Goldstone, CA and Madrid Spain were also required during the descent and landing to reduce the risk of losing the valuable observations. This paper will describe how the NEAR landing trajectory satisfied these requirements and produced a very successful landing.

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